Cooperative Phase Sweep Amplify-and-Forward Transmission

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Abstract—This work presents a new amplify-and-forward (AF) cooperative multiple input multiple output (MIMO) transmission scheme based on phase sweep transmit diversity. In a single hop cooperative link, the relay node imposes a phase sweep on the signal it receives from the source node. This phase sweeping causes fast fading when the signals from the source and relay nodes combine at the destination. On low velocity or static links, this fast fading improves channel code performance. The method used to implement the phase sweeping results in a relay node design that is much simpler than other AF schemes while still providing a comparable performance improvement.

I. INTRODUCTION

Recent advancements in integrated circuit technology have led to the development of very small wireless devices that are being applied to everything from sensor networks to personal communications. One key challenge with this reduction in size is that it is difficult to install multiple antennas on a very small wireless node. Cooperative communication is one way to realize the equivalent of multiple antenna transmission using small, single antenna devices.

An important factor to consider when designing a cooperative communications scheme is simplicity of implementation. In order to achieve the low cost and low energy consumption constraints of most miniature wireless devices, a cooperative communications technique cannot require complex hardware. The goal of this paper is to jointly consider both the system level performance of a cooperative communications technique and its hardware implementation in order to find a cooperative scheme with minimal hardware complexity.

This paper presents a new single-hop cooperative communication technique. Single-hop communication is defined here as a single source node (S) communicating with a single destination (D) with the help of one relay node (R). While cooperative communication is also being explored in the multihop and multi-relay context, single hop transmission is more appropriate for the low complexity focus of this paper.

Cooperative communication can be divided into the decode-and-forward (DF) and the amplify-and-forward (AF) categories. An AF relay node will linearly scale the signal it receives from the source node but will not decode it. Since this reduces the amount of hardware required in an AF relay, it is often suggested that AF is simpler than DF [1]. However, when evaluating AF complexity, it is important to note that most AF schemes require the relayed signal to be delayed by at least one symbol period [1], [2].

This is an important source of additional complexity. The low data rates of sensor networks mean that a symbol period is quite long, making it impractical to realize the delay using analog components. A digital delay requires high speed analog to digital converters and memory. This increases both the cost and power consumption of the relay node.

This paper presents a new AF scheme based on phase sweep transmit diversity (PSTD) [3] that can be implemented without a delay operation using a very simple, all analog relay design. PSTD transmits the same analog signal from two antennas with one of the antennas applying a W Hz phase sweep or frequency offset to its signal. When the two transmitted signals combine in the radio channel, the receiver experiences the equivalent of fast fading with a Doppler frequency of W Hz. In low velocity or static channels, this brings the fading duration back to within the span of the channel interleaver. The result is an improvement in channel code performance.

We present a phase sweep amplify-and-forward (PSAF) technique that creates a similar effect by performing the phase sweeping at the relay node. While phase sweeping at the relay node was originally proposed in [4], the implementation of PSAF in [4] still requires the relay to delay the transmitted signal by one symbol period. This results in the same level of relay hardware complexity as other AF techniques. The all analog relay design presented in this paper is much simpler and simulation will illustrate that it still provides a significant performance improvement.

Section II presents the system model and the implementation details of PSAF are discussed in Section III. Simulation results are presented in Section IV comparing PSAF to the AF technique proposed by Laneman, et. al. [2]. Concluding remarks are made in Section V.

II. SYSTEM MODEL

It is assumed that the cooperative nodes in this paper are used for a low data rate sensor network application where complexity and size must be minimized. As a result, single antenna BPSK modulation is assumed with a bit rate of 19.2 kb/s and a physical layer frame size of 192 bits. The channel code is a simple constraint length 5, rate 1/2 convolutional code with interleaving and soft decision Viterbi decoding. The low data rate will mean that channel fading is flat.

The relay node will be deployed close to the source. This forms a sort of “virtual transmit diversity” arrangement where
the relay will act as a substitute for a second antenna on the source node. This deployment strategy makes it very easy for a network operator to use PSAF on a link-by-link basis to improve communication quality in a sensor or ad-hoc network. The operator would identify a link where communication quality is poor and deploy a PSAF relay next to the transmitting node or nodes.

Placing the relay close to the source is influenced partly by the limited amplification possible from the relay node design discussed in Section III. However, it should be pointed out that the performance of all AF schemes degrade due to noise amplification as the relay is moved further from the source. In addition, only a small amount of $S \rightarrow R$ separation is required in an indoor environment for uncorrelated fading on the $R \rightarrow D$ and $S \rightarrow D$ paths since the source and relay nodes are in a dense scattering environment.

Since the relay is closer to the source node than to the destination node, the ratio of the $S \rightarrow R$ path loss, $A_{SR}$, and the $R \rightarrow D$ path loss $A_{RD}$, $\rho = A_{RD}/A_{SR}$ is much greater than 1. The path loss of the $R \rightarrow D$ and $S \rightarrow D$ paths is assumed to be the same. Flat Rayleigh fading is assumed for the $S \rightarrow D$ and $R \rightarrow D$ paths and flat Rician fading with a K-factor of 10 dB is assumed for the $S \rightarrow R$ path. The choice of 10 dB is somewhat arbitrary but reflects the fact that Rayleigh fading is unlikely for nodes in close proximity. Fading on the cooperative paths is independent.

III. PHASE SWEEP AMPLIFY-AND-FORWARD (PSAF) TRANSMISSION

As described in Section I, the PSAF scheme uses a simple analog relay node design to induce fast fading in the signal received by the destination node. This brings the duration of the channel fades to within the span of the channel interleaver and improves channel code performance.

Fig. 1 shows the relay node circuit connected to an antenna and a lumped element model of that antenna. The circuit reflects an amplified version of the analog signal received from the source node and varies the phase of that reflected signal in a sinusoidal manner at a rate of $W$ Hz.

\[
\Gamma_C = \frac{G_A + j(B_A + B_C)}{G_A + G_C + j(B_A + B_C)} = \frac{(1 - K_G)G_A - j(1 + K_G)B_A}{(1 + K_G)G_A + j(1 + K_G)B_A}
\]

where the antenna admittance is $G_A + jB_A$, the matching circuit admittance is $G_C + jB_C$, $K_G = G_C/G_A$ and $K_B = B_C/B_A$.

The power reflected from the antenna is $P_{\text{ref}} = |\Gamma_C|^2 P_{\text{in}}$, where $P_{\text{in}}$ is the incidence power of the signal received from the source node. Amplification is achieved when $|\Gamma_C| \geq 1$, which occurs when the circuit conductance, $G_C$, is negative. This negative conductance can be realized by a simple amplification element in the relay circuit.

From a communications system design perspective, it is important to know how much amplification is possible from this relay node design. Unlike a traditional AF node design that uses a conventional amplifier, amplification with the design shown in Fig. 1 is limited by circuit stability.

In order to maintain stability, $|G_C| < G_A$ such that $K_G < 1$. However, the closer $K_G$ is to 1, the greater the amplification of the relay node. This is illustrated by plotting the magnitude squared of (1) versus $K_G$ in Fig. 2. This plot shows the amount of amplification possible with the relay node. The plot assumes a typical antenna susceptance of 20, which corresponds to a quality factor of 20. A practical circuit would require $K_G < 0.95$ in order to maintain stability which means the amplification of the relay node would be limited to approximately 30 dB.

![Fig. 2. Relay amplification performance.](image)

Phase modulation is achieved by using a variable capacitor to adjust $B_C$ in order to change the phase of $\Gamma_C$. A plot of the magnitude and phase of $\Gamma_C$ versus $K_B$ is shown in Fig. 3 for an antenna quality factor of 20 and $K_G = 0.95$.

Fig. 3 illustrates another design tradeoff presented by this relay design. As the range of phase variation is increased, amplification is reduced. For example, for a phase modulation range of $\pm90^\circ$, amplification is reduced from approximately 30 dB to approximately 15 dB.
As a result, it is important to establish the smallest possible range of phase variation that will still provide a performance improvement. This will increase the maximum possible amount of $S \rightarrow R$ separation by maximizing the relay node amplification. The amount of system performance improvement that can be achieved with a particular range of phase variation at the relay node will be explored in Section IV.

![Relay node phase modulation performance](image)

**IV. PSAF PERFORMANCE**

Using the system parameters from Section II, simulation is used to compare the performance of the PSAF scheme, non-cooperative transmission ($S \rightarrow D$ transmission only) and the AF technique presented by Laneman and Wornell [2]. For PSAF and Laneman transmission, the transmit power of the source and relay nodes is reduced by 3 dB relative to noncooperative transmission.

The simulation determines bit error rate (BER) at the destination node as a function of average signal to noise ratio (SNR). To model a static channel, new small scale fading values for the $S \rightarrow R$, $R \rightarrow D$ and $S \rightarrow D$ paths are generated at the start of each frame and are then kept constant for the duration of that frame.

For a simulated SNR of $\gamma$ dB, the $R \rightarrow D$ and $S \rightarrow D$ paths experience an SNR of $\gamma$ dB but the SNR on the $S \rightarrow R$ path is $[\gamma+10\log_{10}(\rho)]$ dB, where $\rho$ is the $R \rightarrow D$ to $S \rightarrow R$ pathloss ratio. It is assumed $\rho = 30$ dB. For a path loss exponent of 3, this corresponds to a relay node ten times closer to the source node than to the destination.

Section III showed that relay node amplification can be improved if the phase modulation of the relay node is restricted to a smaller range. As a result, PSAF performance is simulated for a $W = 200$ Hz reflected signal phase modulation that spans the ranges of $\pm 180^\circ$, $\pm 90^\circ$ and $\pm 45^\circ$. It should be emphasized that this phase variation does not have to be synchronized to the source signal in any way.

The simulation results in Fig. 4 indicate that PSAF has the potential to offer a performance improvement similar to Laneman coding. While an improvement is seen even for a phase modulation of $\pm 45^\circ$, Fig. 4 shows a clear benefit to increasing the phase modulation range. Since this can be achieved by reducing the amplification of the reflected signal, the relay should be placed as close to the source as possible. Alternatively, new circuit structures can be explored that are able to reflect signals with a greater phase modulation range [6].

Note that the cooperative BER curves cross the non-cooperative curve at low SNR. This is due to the noise amplification inherent in all AF techniques.

![PSAF performance](image)

**V. CONCLUSIONS**

This paper has presented a new implementation of phase sweep amplify-and-forward transmission that offers a considerable hardware complexity advantage over other AF techniques. The very simple, all analog relay design required by PSAF would allow both the size and cost of cooperative nodes to be dramatically reduced while still offering a performance improvement similar to other AF methods. Analysis of the node design and PSAF performance indicates that this technique will provide the best performance when the relay is deployed close to the transmitting source node.

**REFERENCES**


